Rock Mechanics and Engineering

Editor: Xia-Ting Feng

Volume 4: Excavation, Support and Monitoring

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Foreword

Although engineering activities involving rock have been underway for millennia, we can mark the beginning of the modern era from the year 1962 when the International Society for Rock Mechanics (ISRM) was formally established in Salzburg, Austria. Since that time, both rock engineering itself and the associated rock mechanics research have increased in activity by leaps and bounds, so much so that it is difficult for an engineer or researcher to be aware of all the emerging developments, especially since the information is widely spread in reports, magazines, journals, books and the internet. It is appropriate, if not essential, therefore that periodically an easily accessible structured survey should be made of the currently available knowledge. Thus, we are most grateful to Professor Xia-Ting Feng and his team, and to the Taylor & Francis Group, for preparing this extensive 2017 "Rock Mechanics and Engineering" compendium outlining the state of the art—and which is a publication fitting well within the Taylor & Francis portfolio of ground engineering related titles.

There has previously only been one similar such survey, "Comprehensive Rock Engineering", which was also published as a five-volume set but by Pergamon Press in 1993. Given the exponential increase in rock engineering related activities and research since that year, we must also congratulate Professor Feng and the publisher on the production of this current five-volume survey. Volumes 1 and 2 are concerned with principles plus laboratory and field testing, *i.e.*, understanding the subject and obtaining the key rock property information. Volume 3 covers analysis, modelling and design, *i.e.*, the procedures by which one can predict the rock behaviour in engineering practice. Then, Volume 4 describes engineering procedures and Volume 5 presents a variety of case examples, both these volumes illustrating 'how things are done'. Hence, the volumes with their constituent chapters run through essentially the complete spectrum of rock mechanics and rock engineering knowledge and associated activities.

In looking through the contents of this compendium, I am particularly pleased that Professor Feng has placed emphasis on the strength of rock, modelling rock failure, field testing and Underground Research Laboratories (URLs), numerical modelling methods—which have revolutionised the approach to rock engineering design—and the progression of excavation, support and monitoring, together with supporting case histories. These subjects, enhanced by the other contributions, are the essence of our subject of rock mechanics and rock engineering. To read through the chapters is not only to understand the subject but also to comprehend the state of current knowledge.

I have worked with Professor Feng on a variety of rock mechanics and rock engineering projects and am delighted to say that his efforts in initiating, developing and seeing through the preparation of this encyclopaedic contribution once again demonstrate his flair for providing significant assistance to the rock mechanics and engineering subject and community. Each of the authors of the contributory chapters is also thanked: they are the virtuosos who have taken time out to write up their expertise within the structured framework of the "Rock Mechanics and Engineering" volumes. There is no doubt that this compendium not only will be of great assistance to all those working in the subject area, whether in research or practice, but it also marks just how far the subject has developed in the 50+ years since 1962 and especially in the 20+ years since the last such survey.

John A. Hudson, Emeritus Professor, Imperial College London, UK
President of the International Society for Rock Mechanics (ISRM) 2007–2011

Introduction

The five-volume book "Comprehensive Rock Engineering" (Editor-in-Chief, Professor John A. Hudson) which was published in 1993 had an important influence on the development of rock mechanics and rock engineering. Indeed the significant and extensive achievements in rock mechanics and engineering during the last 20 years now justify a second compilation. Thus, we are happy to publish 'ROCK MECHANICS AND ENGINEERING', a highly prestigious, multi-volume work, with the editorial advice of Professor John A. Hudson. This new compilation offers an extremely wide-ranging and comprehensive overview of the state-of-the-art in rock mechanics and rock engineering. Intended for an audience of geological, civil, mining and structural engineers, it is composed of reviewed, dedicated contributions by key authors worldwide. The aim has been to make this a leading publication in the field, one which will deserve a place in the library of every engineer involved with rock mechanics and engineering.

We have sought the best contributions from experts in the field to make these five volumes a success, and I really appreciate their hard work and contributions to this project. Also I am extremely grateful to staff at CRC Press / Balkema, Taylor and Francis Group, in particular Mr. Alistair Bright, for his excellent work and kind help. I would like to thank Prof. John A. Hudson for his great help in initiating this publication. I would also thank Dr. Yan Guo for her tireless work on this project.

Editor
Xia-Ting Feng
President of the International Society for Rock Mechanics (ISRM) 2011–2015
July 4, 2016

Contents

Excavation Methods

Chapter 1

Excavation

Robert Galler
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1 INTRODUCTION

In the past excavation technologies were mainly driven by the expected ground conditions and the state of the art technologies available in different parts of the world. In principle this situation has not changed a lot, but nowadays many other influencing factors like environmental issues, vibrations, noise, etc. for choosing the best excavation technology have to be considered. The chapter "excavation" deals with the most common excavation technologies, namely NATM and TBM, where a lot of progress was made in the last few years due to intensive research. Furthermore some failure mechanisms which were often observed at different underground construction sites are summarized. As on many tunnel construction sites the excavated materials are still treated as a waste, the outcome of the European research project DRAGON – which was created for developing resource efficient tunneling – shows. The main goal of this related research was to produce high quality raw materials out of the excavated materials, which is of high interest in regions where depositing areas are not available and primary resources for the construction site as well as for the mineral resources consuming industry are rare.

2 EXCAVATION BY NATM

The development of tunneling methods and construction practices within a particular nation is influenced by many geographical, political, social and cultural factors. Such factors include the geographical situation, topography, existing infrastructure and buildings, environment, natural resources, geological and hydrogeological conditions, the demand for underground works, the political, social and economic situation, technical standards, the legal status and competence of owners, the availability of qualified workforce, mining tradition and contractual views.

Situated in central Europe, Austria is and has always been a vital corridor for the transportation of both people and goods. The country is mainly mountainous and partly hilly; large plains and wide valleys are rare.

In terms of tunneling, the geological conditions in Austria are generally difficult and tend to change rapidly along a tunnel route. Tunneling in the Alps is characterized by high overburden and, in some cases, heavily squeezing rock. However large scale underground construction projects are also common in urban areas where the protection of both the population and the natural environment is paramount.

In the 1950s tunnels in the Alps were primarily constructed in conjunction with hydroelectric projects. Since 1970 an increasing number of tunnels for infrastructure have been built. During this period, owners experienced in tunnel design and construction together with specialized contractors developed an on-site decision making procedure, which became common practice in Austrian tunneling.

At this time Austria had a number of brilliant engineers like Rabcewicz, Müller, Pacher, Lauffer, Seeber, and others who greatly influenced and promoted the development of tunneling in Austria with innovative ideas. Their most important contribution was the development of NATM (New Austrian Tunneling Method), which included the observational approach.

Since 1950 new materials, namely shotcrete and rock anchors, replaced the old timber support and a permanent, in-situ concrete lining was provided in lieu of the traditional masonry lining. In addition, the standardized use of synthetic membranes and fabrics significantly improved the quality of tunnels in terms of water tightness. The technological development along with improved engineering practices paved the way for new theoretical explanations to substantiate an economically beneficial design approach.

The Austrian methodology of tunneling is based on a procedure which requires both construction partners to make immediate, joint decisions with regard to ground conditions. The flexibility to make such decisions is incorporated into the contractual framework to ensure an immediate and effective response to changes in ground conditions. The successful application of the NATM is made possible through the collaboration of qualified and experienced owners, designers, contractors and site engineers working with a knowledgeable, experienced workforce within the framework of a suitable contractual model.

Within the Austrian tunneling community emphasis is placed on good cooperation between all parties involved. Technical questions regarding safe, fast and economical tunneling take priority over contractual considerations. This approach is of general benefit to all parties. It is based on a profound technical expertise and a willingness to cooperate. As a general rule, tunneling projects in Austria are executed on the basis of a unit price contract.

2.1 Principles of conventional tunneling

NATM is based on the concept that the ground around the tunnel not only acts as a load, but also as a load-bearing element. Typically, the excavation and support activities are continuously adjusted to suit the ground conditions, always considering the technical/design requirements. The ground reaction, in the form of lining displacements is measured in order to check the stability of the opening and to optimize excavation and support process.

Depending on the project conditions (*e.g.* shallow soft ground tunnel, deep rock tunnel) and the results of the geotechnical measurements, the requirements for a specific support are determined. Contractual arrangements must be flexible to ensure that the most economical type and amount of support is used.

The typical support elements in NATM are shotcrete and rock dowels. Steel ribs or lattice girders provide limited early support before the shotcrete hardens and ensure correct profile geometry. If ground conditions require support at or ahead of the excavation face, face dowels, shotcrete, spiles or pipe canopies are installed as required.

The excavation cross-section is subdivided into top heading, bench and invert depending on both ground conditions and logistical requirements (*i.e.* to facilitate the use of standard plant and machinery). Side drift galleries are provided to limit the size of large excavation faces and surface settlements.

2.1.1 Hard rock conditions

The basis for the design of tunnels in rock depends on both the ground conditions and the use of the tunnel (water, road, railway tunnel, etc.). Tunnels excavated in sound rock are generally horse-shoe shaped, whereas tunnels excavated in poor rock generally require an invert arch to ensure stability. The tunnel is typically advanced by drill and blast following a sequential excavation method (top heading, bench, invert). However if favorable rock conditions are anticipated, full-face excavation can be used. The bench is excavated simultaneously to the top heading, up to a few hundred meters behind the excavation face, providing a ramp for access to the heading. Some distance behind the bench, the invert is excavated. If ground conditions are unfavorable, an invert arch is provided to close the lining, forming a complete ring.

2.1.2 Squeezing rock conditions

Tunnels excavated in weak rock and high overburden exhibit fracturing and large deformations due to high stresses around the opening which exceed the ground

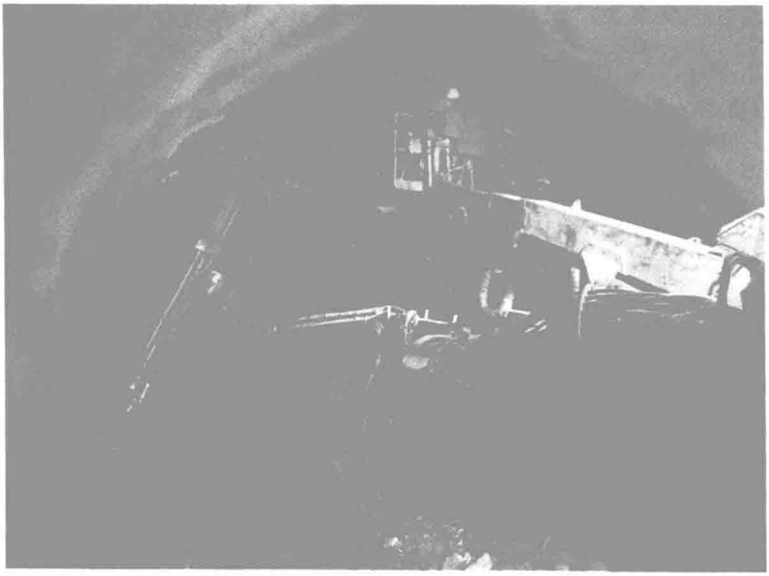

Figure 1 Pilot tunnel in hard rock conditions [Photo: Site Supervision Exploration Tunnel Paierdorf, Koralm Tunnel, ÖBB].

Figure 2 Yielding elements installed in longitudinal slots in the top heading [Photo: PORR Tunnelbau GmbH, Tauerntunnel, ASFINAG].

strength. In order to effectively manage these large deformations, a number of important design parameters must be established. These include definition of the over-excavation required to provide the deformation allowance, as well as the determination of support measures. A support system which allows controlled deformation is chosen to limit the required support resistance and to achieve stability. To increase the shear strength of the rock mass, the key support element is the use of rock dowels. The shotcrete lining thickness is typically 0.2 m to 0.3 m. In case of large displacements longitudinal slots in the shotcrete lining and yielding support elements are placed to allow deformation without damage to the lining. Once the rock pressure is significantly reduced and stabilization of the opening is confirmed by monitoring, the slots in the lining are closed with shotcrete. Yielding elements are integrated into the shotcrete lining. These yielding elements act to limit the normal forces in the shotcrete lining, thus preventing overstressing and preserving the support capacity. Figure 2 shows the use of the deformable support system.

2.1.3 Soft ground conditions

Shallow tunnels in soft ground require the use of both a rigid support and a predetermined sequence of advance. In conventional soft ground tunneling, the emphasis is on a rigid shotcrete lining, a short advance length and a rapid invert closure. If required, the cross section is divided into side and center drifts. Auxiliary measures like dewatering wells, compressed air, jet grouting or even ground freezing are also applied where necessary. In addition to the geological, hydrogeological and geotechnical conditions, the design of tunnels in soft ground must also consider the use of the tunnel, environmental factors and minimizing surface settlements.

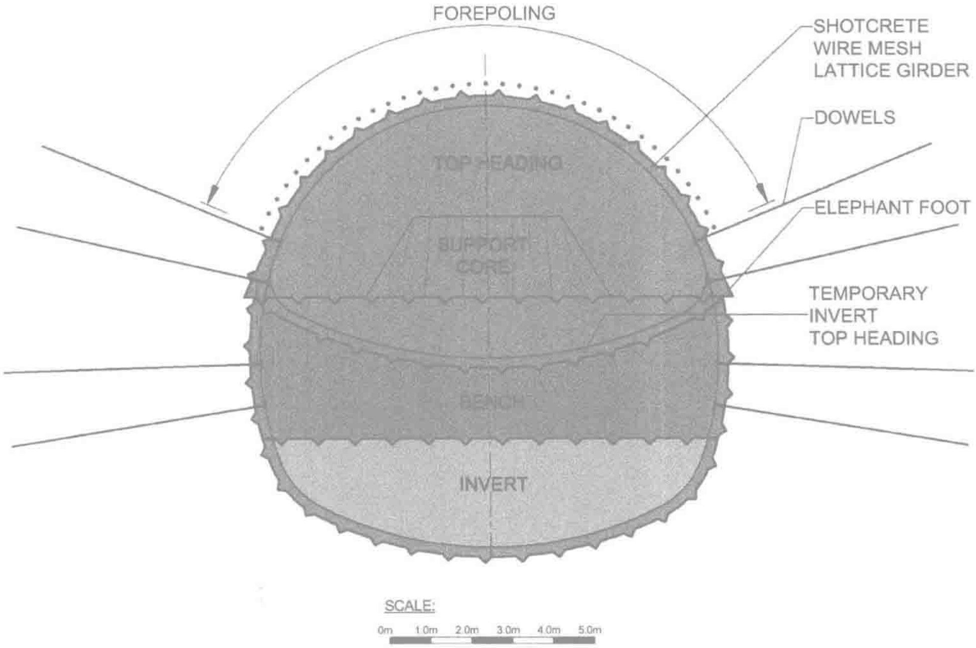

Figure 3 Typical excavation and support in soft ground conditions [NATM – the Austrian way of conventional tunneling; ISBN 978-3-200-01989-8].

The excavation sequence is typically split into top heading – bench – invert. Face support (supporting core), elephant feet, a temporary invert in the top heading and the arrangement of a pipe canopy can be employed.

The length of the excavation rounds for this example is limited to a maximum of 1.0 m in the top heading, 2.0 m in the bench and 4.0 m in the invert. The closure of the temporary invert follows 5.0 m to 7.0 m behind the face of the top heading. The closure of the invert follows 2.0 m to 6.0 m behind the face of the bench. The advance rate is related to the quality of the young shotcrete. Typically it is restricted to 5.0 m in 24 hours in the top heading and 8.0 m in 24 hours in the bench and invert to limit stresses in the primary lining.

The excavation of tunnels with large cross sections in shallow overburden requires that the size of the excavation face be reduced to limit surface settlement. This can be achieved by using an excavation sequence consisting of two sidewall drifts and a center core.

In this example the side wall drifts serve as both a pilot tunnel and a foundation for the crown support. The side wall drifts are advanced individually employing an excavation sequence with a short top heading followed by early invert closure as shown in Figure 4.

Particular attention is given to facilitate the connection of side wall drift linings with the crown support and invert of the core. After breakthrough, or at a substantial distance behind the side wall drifts, Core 1 is advanced as an essentially independent operation, using 1.0 m long rounds and a top heading and bench sequence (see Figure 4). Core 2

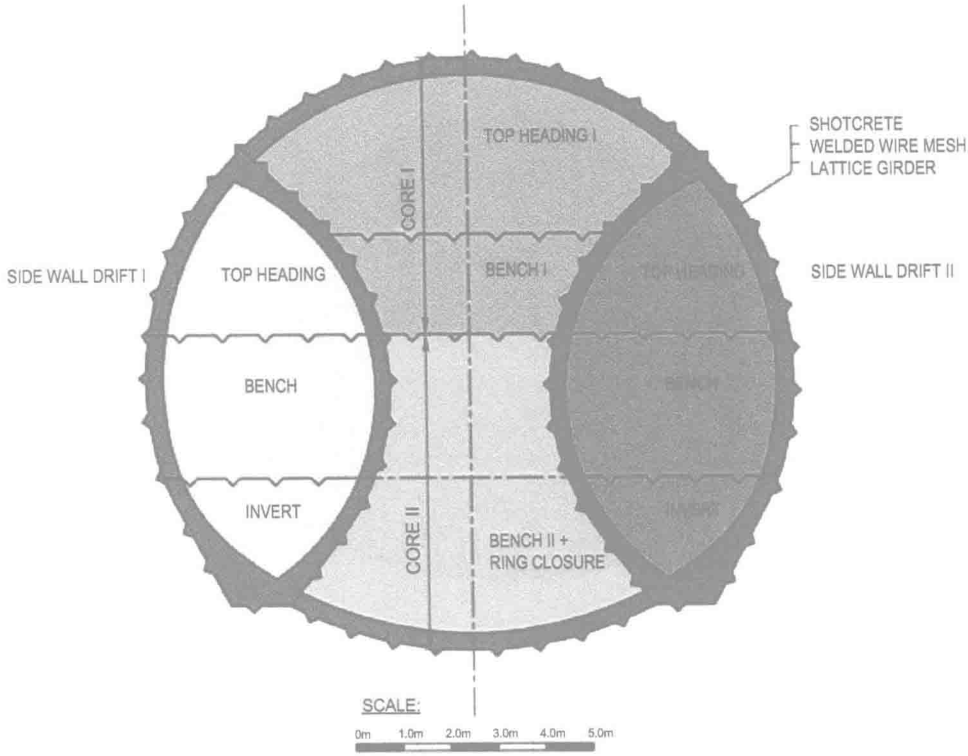

Figure 4 Typical excavation and support for side wall drift method [NATM – the Austrian way of conventional tunnelling; ISBN 978-3-200-01989-8].

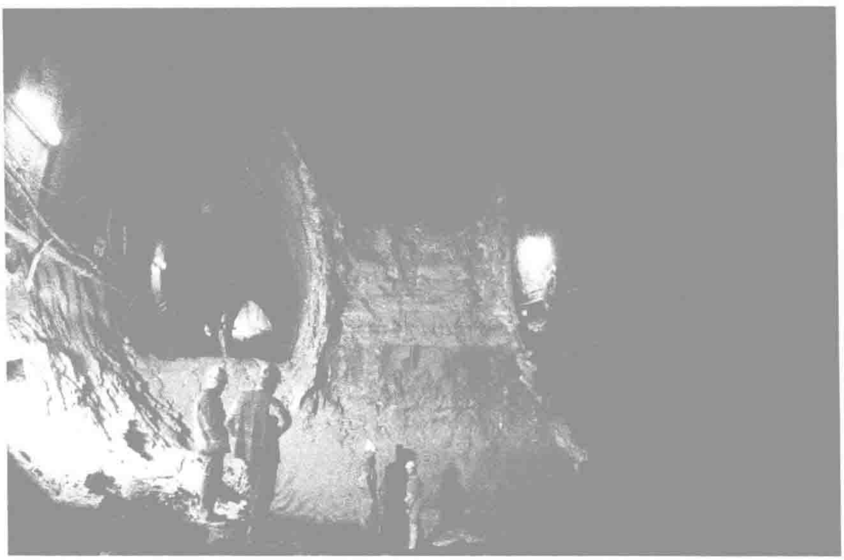

Figure 5 Double track railway tunnel in urban environment [Design Team Lainzer Tunnel LT31, ÖBB].